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DESIGN, DEVELOPMENT AND PRE-FLIGHT TESTING OF THE COMMUNICATIONS, NAVIGATION, AND NETWORKING RECONFIGURABLE TESTBED (CONNECT) TO INVESTIGATE SOFTWARE DEFINED RADIO ARCHITECTURE ON THE INTERNATIONAL SPACE STATION

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The Communication Navigation and Networking Reconfigurable Testbed (CoNNeCT) is a NASA-sponsored mission, which will investigate the usage of Software Defined Radios (SDRs) as a multi-function communication system for space missions. A software-defined radio system is a communication system in which typical components of the system (e.g., modulators) are incorporated into software. The software-defined capability allows flexibility and experimentation in different modulation, coding and other parameters to understand their effects on performance. This flexibility builds inherent redundancy and flexibility into the system for improved operational efficiency, real-time changes to space missions and enhanced reliability/redundancy. The CoNNeCT Project is a collaboration between industrial radio providers and NASA. The industrial radio providers are providing the SDRs and NASA is designing, building and testing the entire flight system. The flight system will be integrated on the Express Logistics Carrier (ELC) on the International Space Station (ISS) after launch on the H-IIB Transfer Vehicle in 2012. This paper provides an overview of the technology, research objectives, payload description, design challenges and pre-flight testing results.

INTRODUCTION

The Space Communications and Navigation (SCaN) Office in the Human Exploration and Operations Mission Directorate at NASA Headquarters sponsored research and technology development in SDRs and communications architectures that missions could take advantage of over the next 20 years. In addition, other US agencies and aerospace communications companies have funded software defined radio research and technology development. Following the announcement of the Vision for Space Exploration in January 2004, NASA began to study and identify the benefits of moving to an SDR-based radio architecture. These benefits include multiple suppliers that could deliver to a common standard, greatly improved spacecraft communications architecture and the ability to better accommodate technology and operations evolution.

By 2007 only a few radio suppliers had developed and flight demonstrated elements of SDRs [1, 2, 3] and had evolved to designing, building and testing brassboard ground demonstrations of

complete flight radio systems. The two missions that flew SDRs were Mars Reconnaissance Orbiter (MRO)[1] and Lunar Reconnaissance Orbiter (LRO)[2]. The inclusion of SDRs was more for hardware validation rather than for the utility of on-orbit reprogrammability. While the missions certainly were aware of the reprogrammable nature of the SDRs, reconfiguration was limited to essential reconfigurations or for demonstrations as part of the mission. In all cases, the missions did not plan to reconfigure to change operating characteristics of the radios.

During this time, researchers were exploring various waveforms analytically and in laboratory experiments, and conducted a short duration flight demonstration aboard Space Shuttle Columbia [3]. SCaN program participants, observing this progress, knowing the potential benefits (e.g., risk mitigation for mission spacecraft), proposed a testbed attached to the ISS to provide the flight demonstration. The testbed gained a quick favorable reception within the predecessor to the SCaN program, and was formulated in 2006 and 2007 and initiated in 2007.

FORMULATION OF THE SDR TESTBED

Besides the few instances of SDRs in missions, SDRs were still a new, unproven technology. Field-Programmable Gate Arrays' (FPGAs') capacities were becoming sufficient to accommodate typical NASA waveforms and the US Department of Defense (DoD) was in the midst of developing SDRs for ground. A key research element underway at NASA was the development of the Space

Telecommunications Radio System (STRS), a reference architecture for SDRs.[4]

During formulation discussions, the STRS team determined the importance that any flight demonstration project should 1) develop SDRs compliant to the STRS Architecture to advance its technology readiness level, reducing the risk for mission adoption, 2) fly multiple radios to demonstrate the applicability of STRS across platforms and 3) demonstrate capability envisioned by future missions.

Studies in 2006 were conducted to assess technology needs of various NASA programs and several key elements were identified: Ka-band operations, adaptable S-band transceivers, on-board networking and future (e.g., L5) GPS signal assessments. These capabilities became the principal elements of the system. Since the radios would be reconfigurable and compliant with the STRS standard, the STRS team envisioned that multiple experimenters could use the system for a variety of experiments, thus as a testbed; experimenters could develop software for the radios for their own objectives, within the constraints of the overall system.

To improve the utilization of STRS and provide sources of STRS compliant radios, multiple radios on the testbed were envisioned coming from both industry and NASA labs. This would provide an initial source of STRS radios for future missions. To contain the cost of flying multiple radios, NASA released a NASA Research Announcement (NRA) to develop and receive the industry provided SDRs. The NRA

offered an opportunity to host SDRs on the testbed and provide time for the developers to access their SDR for their own experimental use. In return, NASA required that the proposer share the development cost of the SDR. After a competitive review and selection, both General Dynamics Corporation and Harris Corporation were selected to develop and deliver SDRs to NASA for the flight experiment. In addition, NASA's Jet Propulsion Lab (JPL) was also funded to develop an STRS SDR. Thus, after the NRA selections, the testbed would host three SDRs, with GD providing an SDR for S-band, Harris providing a Ka-band SDR, and JPL providing a dual-band SDR of both S-band and L-band.

REQUIREMENTS

The requirements for CoNNeCT were derived from formulation objectives and were decomposed into specific Level 1 requirements in the following five main groups:

1. Use reconfigurable systems to validate different communications capabilities and advance the Technology Readiness Level (TRL) to 7 of laboratory SDRs, the STRS standard, proposed waveforms, access schemes, architecture flight software and operational concepts.

2. Test technologies for Exploration Systems Mission Directorate (ESMD) Constellation (Cx) and other NASA mission directorates' communications and networking for risk reduction.

   a. Lunar relay emulation

   i. Ka-band forward link and return links via Tracking and Data Relay Satellite System (TDRSS), at data rates representative of Lunar Relay and/or Lunar network capabilities up to 6 Mbps forward and 25 Mbps return, transmitting up to 100 Mbps internally and/or externally generated, using Single Access (SA) connectivity.

   ii. S-band and Ka-band capabilities, such as S-band low data rate links simultaneously with Ka-band high data rate links, utilizing multiple SDRs.

   b. S-band forward link and return links via TDRSS, including, at minimum, data rates at 72 kbps forward and 192 kbps return, using SA and Multiple Access (MA) connectivity.

3. Demonstrate on-orbit SDR/STRS performance and operations from multiple suppliers.

4. Conduct navigation experiments to include verifying tracking and performance of SDR-based GPS, tracking and performance of TDRSS Augmentation Service for Satellites (TASS)-augmented GPS and TDRSS tracking and ranging.

5. Conduct communications and networking experiments to assess Delay Tolerant Networking (DTN) protocols, on-board routing and potentially other Constellation Command, Control, Communications and Information (C3I) concepts.

The development of the lower level requirements was a combination of a top down decomposition and a bottoms-up capability-driven approach. The top down method was traditional, with the usual challenges and decisions on management of external requirements given the large requirements documents (e.g., ISS ELC). The radios were pre-selected (before the Level 1 requirements baseline) and requirements were largely defined from prior specifications and capabilities. Hence, the level four and five requirements specifications were written, informed the Levels 1 (HQ/Program), 2 (System), and 3 (Flight and Ground System) development and then were updated and expanded to capture the top down decomposition. This approach worked; however, this approach was not the most effective and is not recommended for future developments (Refer to Design and Development Challenges, below).

DEVELOPMENT APPROACH

The development approach for the flight and ground systems minimized the schedule and cost by optimizing the procurement approach including and combination of NASA internal work, Cooperative Agreements and standard procurements. Furthermore, the project minimized schedule and budget resources using a protoflight development approach. This approach included breadboards for most subsystems, an engineering model (EM), a flight model (FM) and no qualification models. The flight system consists of the structure (flight enclosure), three SDRs, the Radio Frequency (RF) subsystem, avionics, thermal control and the Antenna Pointing System (APS).

The specific procurement strategy was as follows. Two of the three Software Defined Radios (SDRs) were developed using Cooperative Agreements, with General Dynamics and Harris Corporation providing approximately half the development costs. NASA JPL (teamed with L3 Cincinnati Electronics) provided the third SDR and RF subsystem including antennas. NASA Glenn Research Center (GRC) provided the structure, avionics, software, thermal, APS and system integration using in-house engineering, manufacturing and test capabilities and procurements. The JPL SDR software was developed by three NASA Centers with the intent to prove out the STRS paradigm for the S-band waveform: JPL provided the Operating Environment (OE) and Goddard Space Flight Center (GSFC) and GRC jointly provided the S-band TDRSS Waveform Applications. Finally, the mission operations required no significant procurement since existing GRC ISS operations capabilities were leveraged.

To buy down development risk, subsystem breadboards and EMs were combined to create several testbeds to conduct the following testing:

- Structural Test Article (STA): Flight-like primary structure in terms of mechanical form and fit; used to test and verify the random vibration loads using mass simulators for subsystems, buying down risk for the system.

- Software Development Systems (SDSs): Breadboard avionics and SDRs with ELC simulators (ISS interface) used to develop and test software. The project ultimately purchased the components to

develop five SDSs, which enabled parallel developments and risk mitigation prior to testing on the Ground Integration Unit (GIU).


Figure 1: Software Development System

Ground Integration Unit (GIU): Replica of the flight system using EM units that have the same function and very similar form and fit; it became the "workhorse" testbed used for software development and formal verification, communication system testing, dry run procedures prior to flight and mission operation procedures, training and tools. GIU was initially configured in a "flat sat" or table-top configuration to enable easy configuration update and was later installed into the STA enclosure to become as flight-like as possible. The GIU bought down significant risk prior to testing on the flight system and enabled parallel development given two robust platforms.

To save resources, only limited flight spares to mitigate higher risks were included in the development. For the SDRs, RF and APS systems, sparing was done at the component level for long-lead electrical components; low

risk items or those that were cost-prohibitive did not have spares. Additionally, elements of the EM SDRs had identical flight parts and provided alternative sparing opportunities. The avionics unit was a new higher-risk development and a spare unit was created; this helped later with system issues. For structures and thermal, sparing was also at the component level (e.g., fasteners).
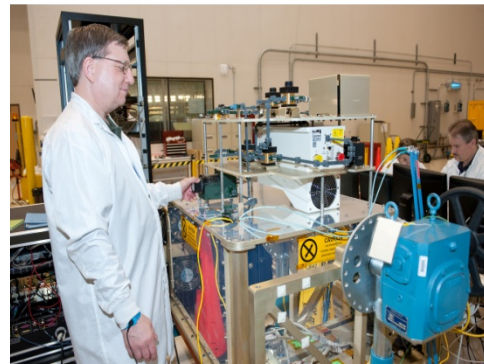
Figure 2: Ground Integration Unit

The overall project schedule from Preliminary Design Review (PDR) to Flight System Ship (ready) was about two years. This is about one year less than a standard development due to the protoflight approach, early development of the radios, and the continuous energy given by the team to complete the work quickly, without compromise to design and certification requirements.

HARDWARE DESIGN

The CoNNeCT flight system (to be called the SCAN Testbed on-orbit) is illustrated in figures 3 and 4. The testbed relies upon the ISS ExPRESS Pallet Adapter (ExPA)[5] to provide standardized structural, electrical and data interfaces with the ISS ELC, the Space Station Remote Manipulator System (SSRMS), and the Japanese Aerospace Exploration Agency (JAXA)

Multipurpose Exposed Palate (EPMP)[6]. Among other items, the ExPA includes the active portion of a Flight Releasable Attachment Mechanism (FRAM), power and data connector panels, Extravehicular Activity (EVA) /Extravehicular Robotic (EVR) interfaces and the payload adapter plate. The ExPA serves as the foundation of the CoNNeCT flight system.
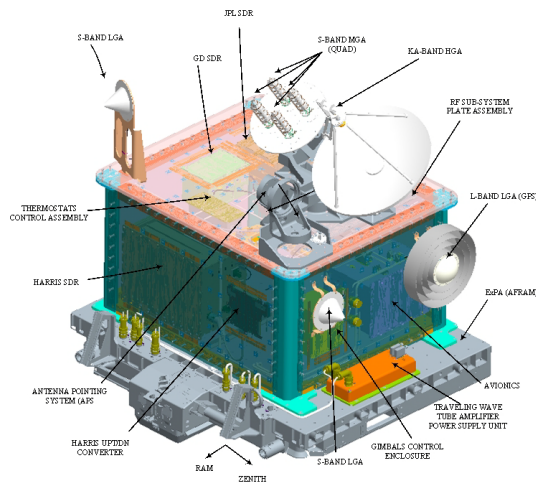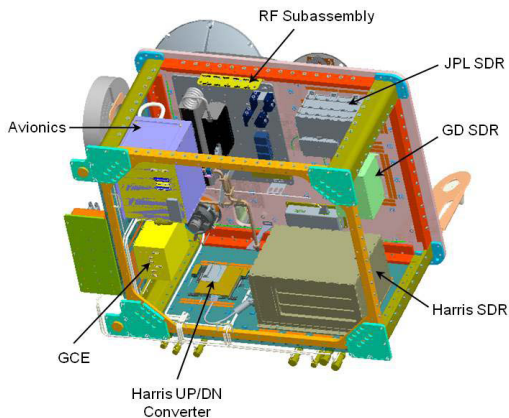

Figure 3 – CoNNeCT flight system

Figure 4 – Flight system without ExPA and non-radiating panels

On the ExPA foundation, the following five additional subsystems are integrated to form the flight system: mechanical subsystem, electrical subsystem, RF subsystem, APS, and SDRs. The SDRs are the principal reason for the testbed,

so they will be discussed in a separate section. The following paragraphs briefly describe the remaining support subsystems.

The mechanical subsystem provides structural support for the other subsystems; its design also allows thermal energy to be rejected to space via three radiating surfaces (starboard, ram and zenith radiators). The subsystem consists of a frame-and-panel flight enclosure, various mounting brackets, fasteners, and multilayer insulation on the two non-radiating exposed surfaces (wake and nadir shields). The mechanical subsystem accounts for 39% of the 339 kg flight system mass.

The electrical subsystem receives a maximum of approximately 500 W of electrical power from the ExPA, conditions it and transfers it to the electrical loads in the system. Digital communication between subsystems and overall system command and control is also provided by this subsystem. The electrical subsystem is comprised of three primary subassemblies [avionics, TWTA power supply unit (PSU), and thermostat control assembly (TCA)] plus resistance heaters and the cabling interconnecting all of the subsystems. Functional interaction of the avionics portion of the electrical subsystem and other elements of the flight system is depicted in figure 5.
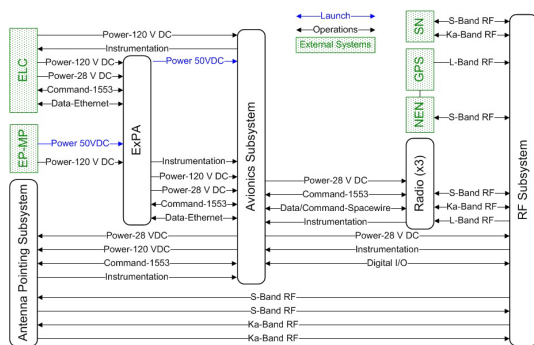
Figure 5 – Functional interactions of avionics with other flight elements

Figure 6 – Integrated RF system

The avionics unit uses a 733 MHz processor and 64 GB of flash memory to operate the flight system. SpaceWire and MIL-STD-1553 buses are employed for command and telemetry as well as data flow.

The RF subsystem consists of an RF plate subassembly, a traveling wave tube amplifier (TWTA), five antennas and interconnecting transmission cable and waveguide. The RF plate subassembly contains Ka- and S-band diplexers, a Ka-band isolator and attenuator and three coaxial transfer switches to route signals to and from different S-band antennas. Two low-gain S-band antennas and an L-band antenna are installed stationary with respect to the flight system. The medium-gain S-band antenna and the high-gain Ka-band antenna are jointly housed on an articulating arm, the APS, for pointing. The RF subsystem and its interfaces are graphically depicted in figure 6. Functional interactions of the RF subsystem are also shown in figure 5.
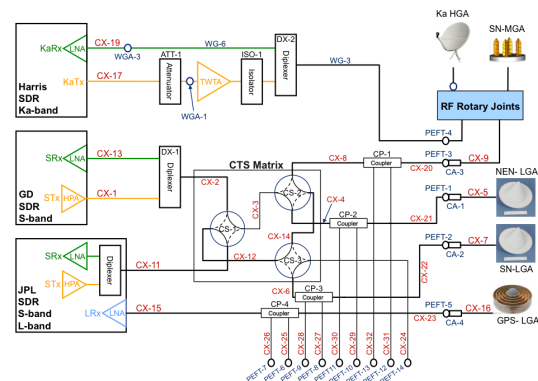
The APS is used to point the medium-gain S-band and high-gain Ka-band antennas for communication with the TDRSS. In addition to a launch restraint and thermal control resistance heaters, two other main subassemblies combine to complete the APS: the integrated gimbal assembly (IGA) and the gimbal control electronics (GCE). The IGA contains two rotary actuators – one each for local elevation and azimuth adjustment. The actuators in combination with the arm mechanism in which they are housed enable precision pointing of the antennas over a large viewing area. Restrained by physical hardstops to limit irradiation of ISS elements, the IGA rotation spans 174 degrees in elevation and 76 degrees in azimuth. The resultant boresight sweep limits are shown in figure 7. This field of view allows the testbed to satisfy key availability requirements for monthly Tracking and Data Relay Satellite (TDRS) contacts.
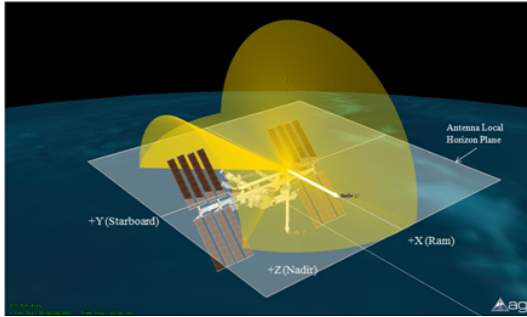
Figure 7 – Boresight sweep limits

Using a MIL-STD-1553 interface, the GCE provides the power, control and telemetry path between the IGA and the avionics subassembly. Position and rate commands are sent from the avionics software to the GCE which then translates and sends the appropriate step commands to the actuators. Optical encoders on each actuator provide position indication telemetry that is transferred through the GCE to the avionics. Because of the wide beam width of the medium-gain antenna, TDRS S-band links are easily established using open-loop pointing algorithms in the avionics software. However, for Ka-band communication with a TDRS, closed-loop control based on signal feedback from the Harris SDR is used to accurately point and track using the APS.

SOFTWARE DEFINED RADIOS

The SDRs are the technology core of the flight system, representing advancement in both SDR technology and the STRS Architecture. The three SDRs developed by Jet Propulsion Lab, General Dynamics and Harris Corporation each adhere to the functional diagram shown in figure 8. The functional diagram illustrates three key elements of each SDR: a general purpose processor module (GPM), a signal processing module (SPM) and a Radio Frequency (RF) Module (RFM). Each SDR is consistent with this type of architecture; however, specific implementations differ for each radio.
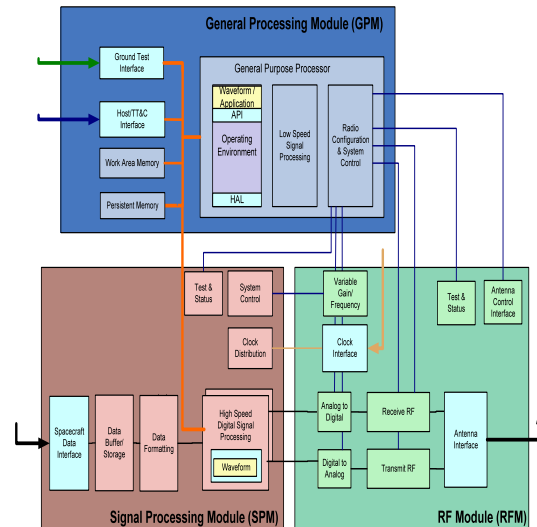

Figure 8 - General SDR architecture

The GPM contains the general purpose processor and associated memory elements for application processing and radio control. The STRS OE runs within the GPM to control the waveforms and other radio functions and platform services throughout the SPM and RFM. The GPM controls loading the waveform from persistent memory (e.g., Electrically Erasable Programmable Read-Only Memory or EEPROM) into the processor or FPGA as designed. Portions of the waveforms can run within the GPM or SPM and are abstracted from the underlying hardware by the STRS Standard. The SPM includes the hardware for the high speed signal processing performed in each radio, in this case, by Xilinx FPGAs. Clock management and distribution functions of the SPM are distributed throughout the SPM and other modules. Finally, the RFM contains the digital to

analog (DAC) and analog to digital (ADC) conversion elements and signal conditioning circuits to the RF interface at the appropriate frequency.

The software architectures are also similar among the three SDRs. Each conforms to the STRS Architecture [4] software interface depicted in figure 9.
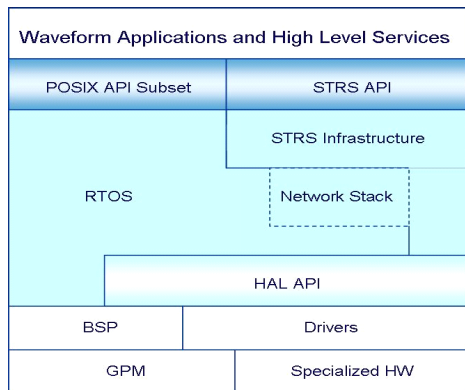

Figure 9 – STRS Software Architecture

The STRS OE manages the functions within the SDR, including command and telemetry, inter-process communications among software elements, and control functions such as loading and unloading the waveforms from memory and executing the waveform. The key element of the software architecture is the application programming interface abstraction between the waveform application and the underlying hardware. User applications access the real time operating system (RTOS) of the operating environment through a Portable Operating System Interface for Unix (POSIX) interface and the waveforms access remaining OE functions through a set of application programming interfaces (APIs) defined by the STRS Architecture (STRS API). Once a user waveform application is loaded on a platform, the POSIX and STRS APIs provide the software interfaces to the underlying hardware.

On the firmware interfaces within the FPGA, the STRS Standard calls out requirements for FPGA signal abstractions between the application and the platform hardware provided by the platform developer and certain documentation of abstractions for hardware resources (e.g., FPGA, DAC, ADC) available for future waveform developers.

The flight SDRs each utilize a modular, stacked configuration and are shown in figure 10.

Figure 10 – Flight SDRs

A summary of the SDR performance and design characteristics is shown in figure 11.

SDR	JPL	GD	Harris
General Purpose and Signal Processing Modules	66 MHz SPARC processor and two Xilinx Virtex II FPGAs	60 MIP Coldfire processor and one Xilinx Virtex II Pro FPGA	700 MIP Power PC processor and four Xilinx Virtex IV FPGAs
RF Module	Two (I/Q) 10-bit 50 Msps DAC and one 12 bit 50 Msps ADC; S-band Duplex (2.1-2.2 GHz, 6 MHz tuning) and GPS receive at L1, L2, and L5	S-band Duplex (2.1-2.2 GHz, 6 MHz tuning)	Two 12-bit 300 MHz DAC and one 300 MHz ADC. Ka-band (transmit: 25.5-25.7 GHz, 225 MHz tuning, receive: 22.5-22.7 GHz, 50 MHz tuning).
Memory Units	128 MByte SDRAM and 512 MByte flash	128 MByte SDRAM, and 4 MByte EEPROM; also 1 MByte Chalcedonide RAM as experiment	256 MByte SDRAM
Operating Environment	RTEM operating system; OE complies with STRS, v1.02	VxWorks operating system; OE complies with STRS, v1.02	VxWorks operating system; OE complies with STRS, v1.02
Command & Telem	MIL-STD-1553	MIL-STD-1553	SpaceWire
Data Format	SpaceWire	Spacewire	SpaceWire
Data Rate Class	10's Mbps	10's Mbps	100's Mbps
Output Power Amplifier	10W	10W	Ka convertor drives 40W TWTA

Figure 11 – SDR Characteristics

BUS SOFTWARE DESIGN

The CoNNeCT SCAN Testbed avionics flight software works in conjunction with the software resident on the flight SDRs as well as ground software commands received via the interface with the ISS ELC. The avionics flight software is "class C" in accordance with NPR 7150.2 – NASA Software Engineering Requirements. A layered architecture is employed that separates SCAN Testbed application code from other layers such as hardware interfaces, component drivers, and the operating system. Using over 100,000 lines of mostly C++ code (comprised of third-party and in-house elements), the avionics flight software satisfies 66 allocated requirements at the software subsystem level that decompose into additional lower-level software requirements. In operational mode, the flight software manages the following eight states: primary-path-ready, initialization, ready, experiment, maintenance, off-nominal, shutdown, and safe. The functions associated with the states can be grouped as command and control, housekeeping and telemetry, fault management, experiment management, timing, and interface management. To simplify the flight software design, all safety-critical commands are issued from the ground; the flight software processes cannot issue these commands independent of ground initiation. To maximize flexibility for future experiments, the flight software is designed so that updated versions of the software – including the kernel – can be uploaded on-orbit.

EXPERIMENT OPERATIONS

Once on-orbit, the CoNNeCT SCAN Testbed will be available to experimenters from NASA, industry, academia and other organizations. Based on announcement of opportunities offered by NASA, experimenters will propose investigations to conduct using the SCAN Testbed. Experiments will entail new software applications that run on the SDRs or within the flight computer (avionics) along with experiment specific ground hardware or

software. The experiment software applications will demonstrate new communications signal formats (e.g., modulation, coding), networking (e.g., on-board routing and DTN) and assessment of navigation techniques based on Global Positioning Satellite (GPS) signals at L1, L2, and the emerging L5 GPS frequencies.

Once a proposal is submitted to NASA, an Experiment Review Board will assess the objectives and advancements proposed and recommend experiments for use with the SCAN Testbed that meet the solicitation criteria. Once approved, experimenters will begin development of their new experiment application and ground hardware. After development has progressed beyond the design and initial development stage, experimenters will be provided access to the SDR and avionics breadboards and engineering models at NASA GRC to continue, refine and complete their waveform or avionics application development. When an experimenter completes their SDR application, the waveform will be tested for STRS compliance and verified for operation with the flight system. After verification, the application software will be uploaded to the flight system for on-orbit experiment operations.

To conduct the on-orbit portion, experimenters will generally work from the Experiment Center at GRC working closely with the CoNNeCT Control Center. Experiment specific ground hardware will reside at the Experiment Center.   The Experiment Center is linked to the Space Network (SN) Control Center where experiment data is exchanged with White Sands Complex (WSC) and transmitted to CoNNeCT via

TDRSS. Experimenter hardware will send and receive data directly with the SCAN Testbed through the CoNNeCT ground system infrastructure.

As shown in figure 12, experiment data links at Ka- and S-band exist between CoNNeCT and NASA's TDRSS and WSC ground station or may use an S-band direct to ground link (not shown in figure). During pre-flight testing, simulators are used for the ELC interface and ISS command processing.
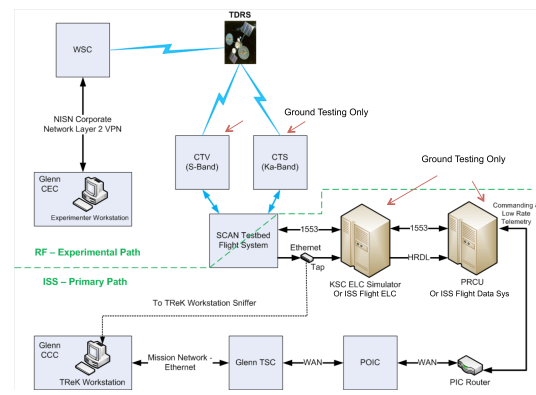

Figure 12 – Experimenter-TDRSS Interfaces for Pre-Flight Testing

ISS AND HTV INTEGRATION

A standard ISS integration approach is used via the Johnson Space Center (JSC) Payload Integration Manager (PIM), with some extension of prior work since CoNNeCT is the first ELC payload installed on-orbit. The carrier physical interfaces are depicted in figure 13 and the HTV launch processing is shown in figure 14 (similar to Kennedy Space Center). The HTV delivers its cargo to the vicinity of the ISS where the ISS robotic arm operations conduct many transfers and installation.
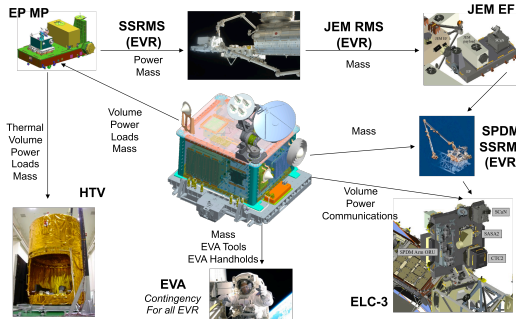
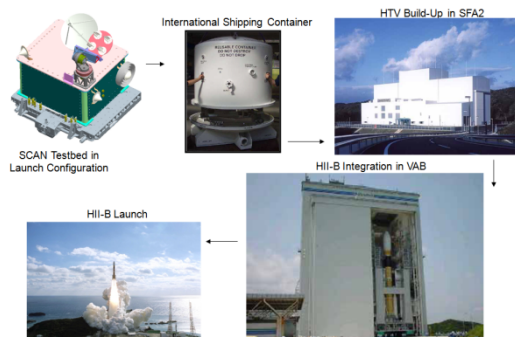*Figure 13 - ISS and HTV Carrier Interfaces*

Figure 14 - HTV Launch Site Processing

DESIGN AND DEVELOPMENT CHALLENGES

Numerous challenges occurred during design and development of the CoNNeCT flight system. Many of the difficulties were rooted in an unconventional method of requirements development. As noted earlier, level 4 and 5 requirements existed (and hardware was even purchased) before level 1, 2 and 3 requirements were adequately established. Some examples of requirements-related design problems are presented below.

APS "Heritage" Hardware
When the APS was procured, the level 3 requirements were underdeveloped, so the level 4 procurement specification was based mostly on what heritage hardware could be obtained to meet perceived cost and schedule constraints. A purchase order (not a development contract) was issued for an integrated antenna pointing system based on the actuators and gimbal control electronics (GCE) used on a previous NASA mission. The vendor had provided the actuators and GCE for the earlier mission, but the heritage integrated gimbal system was not built by the vendor; it was developed in-house at the Goddard Space Flight Center (GSFC). The CoNNeCT purchase order (PO) relied on the vendor to produce an integrated APS based mainly on the previous mission's requirement set, which turned out to be inadequate when the level 3 requirements were completed and flowed to level 4. As a result of the inadequate requirements and the lack of integration experience at the vendor (and partially due to the PO contracting mechanism initially chosen to save two weeks of procurement time), thirteen change orders (with cost and schedule growth of $3.3M to $6.5M and 15 to 23 months, resp.) and intensive interaction with the APS vendor was required to finally produce a useful APS for CoNNeCT.

Structural Redesign and Margin
As discussed above, development of the SDRs was initiated by NASA Headquarters before the CoNNeCT project was fully established. As a result, structural and loads requirements were immature and were not adequately represented by the level 5 vendor specifications; the SDRs were underdesigned for the environments that would have given the best system-level optimization of primary structure. As a result, the system structural team was required to repeatedly craft their design around the SDR constraints. Multiple

design iterations were needed with fairly high-fidelity numerical models to eventually demonstrate adequate structural margins.

ISS ELC Co-development
Because the ISS ELC was being developed at nearly the same time as the CoNNeCT flight system, the level 2 ELC interface requirements were subject to serious perturbations after CoNNeCT tried to finalize level 3 requirements. When the ELC reduced its total payload 28-volt power capacity, the CoNNeCT electrical team had to adopt a new basic architecture that included a 120-volt-to-28-volt DC-DC converter to power the TWTA. Because the addition was late in the development cycle, mounting surface space in the system was scarce and the new TWTA power supply unit (PSU) had to be located outside the primary flight enclosure. Inconvenient assembly constraints resulted due to the final PSU location.

FRAM Non-linearity
Simultaneous with learning that the ELC was reducing power availability, the CoNNeCT design team learned that a misunderstanding between JAXA and ISS caused the EPMP-to-FRAM interface to be improperly labeled. The H-II Transfer Vehicle (HTV) ICD with JAXA specified the launch loads at the interface between the EPMP structure and the passive FRAM. The ISS team had instructed that the launch vehicle interface was on the surface of the active FRAM. (JAXA installs the passive FRAM on the EPMP; the active FRAM is located on the bottom of the ExPA.) The passive FRAM is relatively stiff, so the JAXA specification could be applied to the passive FRAM surface with little error. However, the gap between the

passive and active FRAM introduces a non-linearity in the loads transfer function; a translational non-linear uncertainty factor of 1.5625 and a rotational non-linear uncertainty factor of 2.0 were subsequently levied on our launch acceleration loads. An unclear interface definition caused the structural design team to have to restart their design cycle.

The above examples are no surprise to the experienced space system design engineer. A major complicating factor early in the development was that relatively few people working the issues had significant space flight design experience. This was corrected by PDR with the introduction of very experienced leaders and engineers.

ASSEMBLY AND INTEGRATION

The CoNNeCT flight subsystems each had their own development challenges and associated schedule for completion. As a result the subsystems were not available for system integration at the same time. This impacted the nominal physical and analytical integration processes and the project developed revised implementation methods to enable forward progress on the system. As a result, CoNNeCT revised the system integration and test schedule to optimize it based on which elements were available to enable a given test activity. The following describe some of the top challenges and their resolution.

System Integration Review
NASA policy requires a System Integration Review prior to installation of flight subsystems. Since not all subsystems were available, this requirement was waived and an alternate

process was developed. Each subsystem was subject to an Acceptance Review (AR) to verify the hardware and documentation and an Integration Review (IR) to verify the system was prepared for integration (physical, processes, etc.). Hence, the SIR intent was met via incremental ARs and IRs. This enabled the flight assembly to mature as soon as subsystems were ready. To preserve schedule, lower risk analytical products were completed after the physical integration.

Avionics Unit

Due to issues associated with the power filtering, digital interface and thermal control custom cards (five total), the flight avionics unit (the payload's core processor) was delayed by months. The project recovered most of the schedule by installing the back-up avionics unit first, since it did not require environmental testing and was available six weeks sooner. This enabled critical software and communication testing to proceed on schedule, including TDRSS Compatibility. The flight certified avionics unit was installed prior to the first system environmental test.

Antenna Pointing System

As a result of the development issue explained above, the APS experienced significant schedule delays summing to approximately four months late on delivery. In anticipation, it was decided before CDR to create a dynamic simulator of this model to proceed with system vibration and thermal/vacuum (T/Vac) testing, which created schedule relief to complete APS delivery. Significant resources were used on the dynamic simulator for the IGA, since the structural dynamic models of simple geometries did not adequately simulate

the loads from the APS back into the system. Further details are below in the environmental testing section. For T/Vac testing, the solution was simpler since the IGA base was the only element required to validate the thermal model.

FUNCTIONAL TESTING

The SCAN Testbed is a complex system of highly integrated analog and digital communication subsystems. Functional testing was frequently performed after assembly to demonstrate increasing levels of communication between subsystems and integrated avionics performance. Similar functional testing was performed before and after system-level environmental tests. Some problems were to be expected at the beginning of post-assembly integrated testing. However, three significant problems that were encountered (and ultimately resolved) were not expected. A short description of each problem and its resolution follows.

SpaceWire Cables

As mentioned, the CoNNeCT flight system uses the SpaceWire standard for SDR-avionics data transfer and for command and telemetry on one SDR. SpaceWire is an established standard and is in use by other NASA, ESA and JAXA projects. The SpaceWire cable procured for the CoNNeCT flight system is from a major supplier and is representative of the cabling commercially available. However, because SpaceWire cable is less robust than typical aerospace cabling, the cable fabrication and installation techniques initially used on the flight system led to cables shorting to connector backshells, damage to inter-wire Teflon insulation and intermittent loss of data links

between subsystems. Although not readily available in the literature, special fabrication, handling and installation techniques in use at the GSFC were employed to eliminate the undesirable performance. For example, figure 15 shows the special foam padding and generous bend radius that was used when the cable was supported by tie-wraps so that the internal insulation between wires would not be compromised due to Teflon cold-flow over time. Dissemination of other special techniques to use with SpaceWire cable is planned for forthcoming publication.
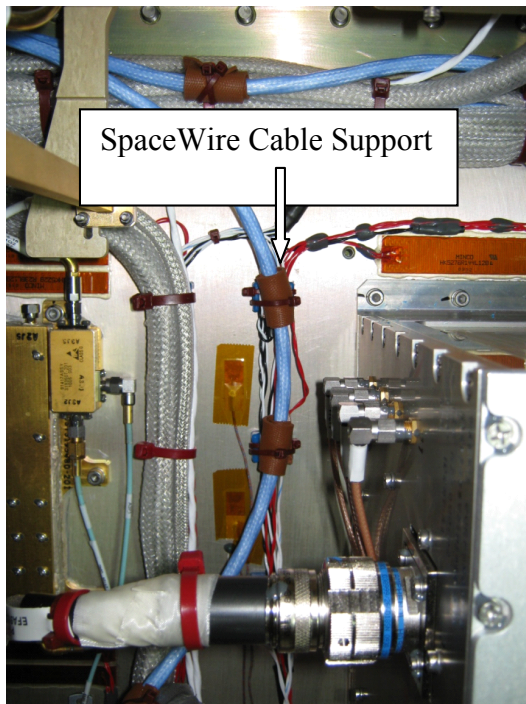
Figure 15 – SpaceWire Cable (blue)

SpaceWire Firmware
The SpaceWire board in the avionics unit was procured from a major commercial source. After uncovering performance issues in how the vendor implemented the combination of SpaceWire and PCI standards on the board, several attempts were made to correct the problem through changes in the vendor firmware. After four unsuccessful iterations, the fifth change yielded an acceptable firmware implementation that provided increased SpaceWire bus performance.

Digital Input/Output Firmware
A similar flawed firmware situation was encountered on the digital input/output (DIO) cards procured for the avionics unit – again from a major supplier of aerospace electronics boards. During integrated testing of the flight system, inadvertent power-on of subsystems was observed. Detailed bus-level troubleshooting revealed that, despite the avionics software correctly commanding the DIO state, within milliseconds additional bus traffic would cause the board to self-corrupt and change the set state to an uncommanded configuration. Working with the vendor, a corrected version of firmware was obtained (by replacing the FPGA and recertifying the cards at the subsystem level) and stable, reliable DIO performance was finally obtained.

ENVIRONMENTAL TESTING

After assembly and successful functional testing, the CoNNeCT flight system was subjected to system-level vibration, thermal-vacuum (T/Vac), and electromagnetic interference/ compatibility (EMI/EMC) tests. (Note: Acoustic certification was accomplished via analysis with launch provider concurrence.) As mentioned above, due to the delayed delivery of the APS, the vibration and T/Vac tests were conducted without the APS installed. For the vibration test a high-fidelity dynamic simulator, including simulated antennas, was constructed to provide the correct dynamic loads for critical

subassemblies in the flight system. The simulator was designed and modal tested to show that the resultant loads imparted to critical subassemblies would be dynamically similar to within 5% on fundamental frequencies, 10% on higher-order frequencies, and 10% on Grms acceleration values with good modal shape correlation and good acceleration spectral density (ASD) peak and phase correlation. These design criteria were synthesized in the spirit of NASA-STD-5002 and ISS document SSP 52005D. In the T/Vac test, the arm of the IGA dynamic simulator was removed to enable more accurate control of the thermal boundary condition at the starboard radiator. (This would have been desirable even if the flight IGA had been available.) A GCE mass and thermal simulator was also fabricated and installed for the first two environmental tests (vibration and T/Vac). System EMI/EMC testing occurred only after APS (IGA and GCE) installation on the flight system was complete. Pre- and post-test system functional tests were performed to verify no adverse effects were introduced by system environmental tests.

System vibration testing was conducted at the NASA GRC Structural Dynamics Laboratory. As defined in NASA-STD-7001, the project used a protoflight test approach with force-limited control to avoid over-test. Most subsystems were tested to maximum flight loads + 3 dB prior to system integration. The integrated test inputs for each of the three axes were as follows: x-axis 5.59 Grms, y-axis 5.69 Grms, and z-axis 5.31 Grms. Spectral representation of the test inputs showing predicted and actual force-limiting notches are shown in figures 16-18.
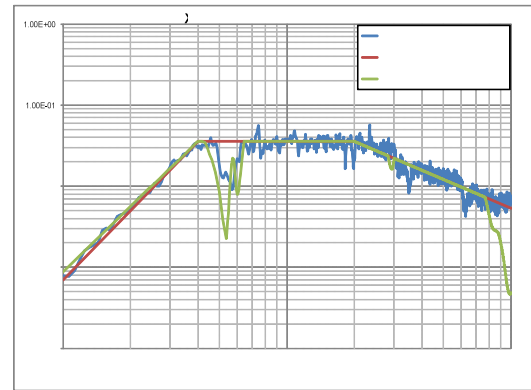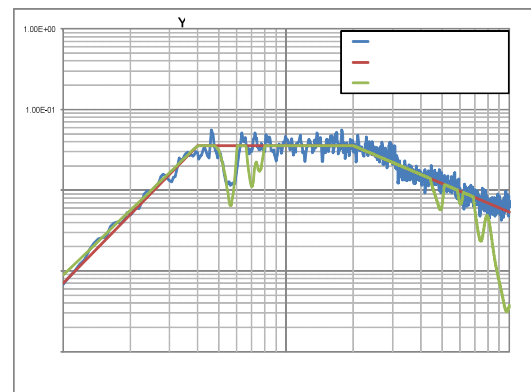

Figure 16 – x-axis test input
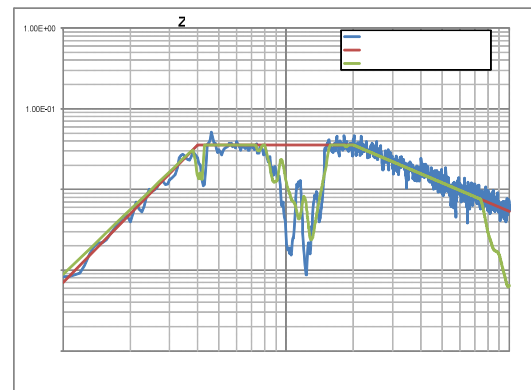

Figure 17 – y-axis test input

Figure 18 – z-axis test input

After system-vibration testing was complete, post-test functional checks were nominal. Post-test analyses concluded that the flight system was certified for random vibration loads.

The system T/Vac test was performed in Vacuum Facility 6 at NASA GRC.

During the test, the flight system was subjected to four mission-based thermal cycles at vacuum (less than 1×10^{-6} torr) including hot (+45 $^{\circ}$C) and cold (-15 $^{\circ}$C) soaks and power-off/on demonstrations per the thermal system model predictions. Most subsystems were tested to six T/Vac cycles prior to this test. The flight system is pictured under test in figure 19.
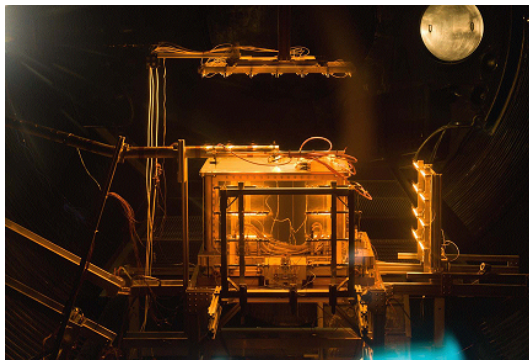

Figure 19 – Flight system in T/Vac

During testing, thermal transition periods were accomplished more efficiently than planned, so the actual total test time was approximately 222 hours (42 unpowered, 180 powered). Post-T/Vac functional checkout was completed successfully. The JPL SDR required more testing to allow calibration measurements since the TDRSS waveform was not part of subsystem testing. In the nine days of T/Vac testing, only four problem reports were filed. One of the four was eventually traced to a potential thermally induced hardware issue.

Investigation of a different problem report uncovered poorly soldered connections on two boards within one of the SDRs. After T/Vac testing, the boards were removed from the still-installed SDR, reworked at the vendor, recertified by test and reinstalled. Because of the serviceable design

configuration, the nature of the removal and reinstallation did not require retest at the system level. Analyses concluded that the flight system was certified for the mission thermal environment.

The final system-level environmental evaluation was the EMI/EMC test. This test was conducted in the NASA GRC EMI laboratory. Test requirements were derived from ISS documents SSP 57003, SSP 57003-ELC, SSP 30237 and SSP 30243. (Prior to system-level testing, a number of subsystem-level EMI/EMC tests were also conducted for risk mitigation.) As summarized in figure 20, the system-level test addressed radiated and conducted emissions, AC and DC magnetic fields and radiated and conducted susceptibility. Five different flight system operational modes were configured during testing. The flight system is pictured in the EMI laboratory in figure 21.

Interfaces Energized During the Test	EMI-EMI Test Designation										
	RE02	AC Mag	DC Mag	CE01	CE03	CS01	CS02	CE07	RS02	CS06	RS03
+120 VDC Operational Power Lines	X	X	X	X	X	X	X	X	X	X	X
+28 VDC Operational Power Lines	X	X	X	X	X	X	X	X	X	X	X
+120 VDC Contingency (heater) Power Lines			X			X	X	X		X	

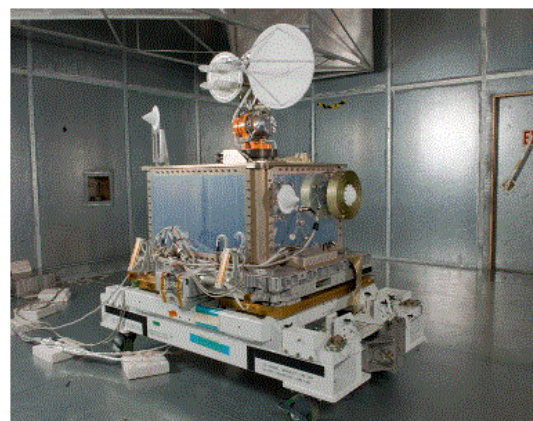*Figure 20 – EMI/EMC Test Summary*

Figure 21 – System EMI/EMC Test

During the three weeks of 2-shift EMI/EMC operations, three conducted susceptibilities were noted on the

avionics unit and one conducted susceptibility was observed on an SDR. In all four cases, previous interface testing with the ISS ELC simulator showed the actual electrical transient characteristics to be less severe (and acceptable) than the EMI/EMC test conditions, so no modifications to the flight system were required. System-level testing additionally confirmed one expected conducted emission exceedance on the 120-volt power lines during initial power-on. Previous ELC simulator testing also showed actual integrated in-rush current would be acceptable for flight, so no flight system change was warranted. Radiated susceptibilities were noted on SDRs near radio operating frequencies; evaluation of the data showed this to be an expected condition given the EMI/EMC test levels. The actual on-orbit environment is not expected to present similar noise emitters. Flight system self compatibility was successfully demonstrated at the end of the EMI/EMC testing.

Exceedances observed during EMI/EMC testing were evaluated and deemed to be of minimal impact to payload flight operations with acceptable risk.

PERFORMANCE TESTING

In addition to standard environmental tests for a typical flight system, users of NASA's SN also conduct a compatibility test to assess performance and verify operations with both the TDRSS and WSC ground system hardware. A series of communications tests are conducted to measure aspects such as tracking and acquisition thresholds of the radios and link performance, and to ensure transmitter

spectrum quality meets transmitter license requirements.

There were two new aspects to the compatibility testing for CoNNeCT. First, as NASA's first Ka-band TDRSS user, CoNNeCT exercised the new Ka-band compatibility test process and equipment. This test included verifying the operational service at WSC, including a high rate data path from WSC to GRC. These connections are shown in figure 12. Second, CoNNeCT is the first SN user flying SDRs. Compared to typical users having a command and telemetry link and a science data return link, the number of selectable configurations of the CoNNeCT's SDRs combined with the multiple antenna paths proved to be a challenge during compatibility testing. With the current set of one launch waveform file for each SDR, CoNNeCT has over 100 different "waveform" definitions, each requiring a unique configuration code at WSC to identify the TDRSS service, data formatting, modulation and coding aspects of both the forward link from WSC to CoNNeCT and the return link from CoNNeCT to WSC.

The TDRSS Compatibility Test was completed in three phases of approximately one week each to align with the subsystem test schedule and the system capabilities. Minor incompatibilities were uncovered during the first test phase, which were corrected through firmware updates and retested during the subsequent phase. This is an example of the value of the reconfigurable nature of the radios. The inability to modify the firmware would have resulted in performance

degradations in certain operational modes.

In addition to the TDRSS Compatibility Test, a second communications system test entailed verifying the gimbal motion open-loop and closed loop Ka-band pointing algorithm. For communication using the gimbal mounted, medium gain S-band antenna (and 36º for 3 dB beamwidth) link analysis indicates that pointing the antenna based on the ephemeris information of ISS and TDRSS is sufficient to close the link without fine pointing (i.e. open-loop). For Ka-band communications however, the link requires that the gimbal point the Ka-band antenna (1.6º for 3 dB beamwidth) using a closed loop pointing algorithm. The pointing algorithm uses a signal strength indicator from the Harris SDR receive waveform and moves the antenna along the antenna pattern gradient to maximize the received signal strength. Prior to testing with hardware in the loop, a detailed simulation was created that exercised all closed loop functions. This simulation was validated with actual hardware and now is a reliable tool to verify algorithm changes.

The antenna pointing system test included the avionics (hosting the algorithm), the GCE, the gimbal, and the gimbal-mounted S-band and Ka-band antennas.

The open-loop testing characterized the gimbal motion across each axis, and included measuring insertion loss throughout the rotary joint travel range and verifying the mechanical and electrical antenna boresight alignment. Closed-loop testing used a portable near-field range within the clean room and a

source transmitter on a moveable platform to emulate the TDRS. Figure 22 depicts the closed loop test setup with the TDRS emulator cart (foreground) and the flight system (60 ft away in the background). The cart hosts a planar scanner system with a waveform generator and transmit horn attached. The cart follows a predetermined path on the floor and combined with the planar scanar motion, simulates the ISS movement relative to TDRS.

The waveform generator provides a forward link signal to the Harris SDR to demodulate and trigger the signal strength indicator. The pointing algorithm monitors the received signal strength and points the flight system antenna to follow the cart along its path. The cart path and planar scanar movement is determined to provide antenna slew rates expected during a typical TDRSS pass.

Figure 22 – TDRS Emulator Cart and Flight System and Closed Loop Testing

SUMMARY AND CONCLUSIONS

The design, development and test of the CoNNeCT system represents both a technical and programmatic achievement. The NASA and Industry partnership in developing and integrating

Software Defined Radios into the experiment is an example of the collaboration required for future missions. The technical developments; including demonstration of simultaneous waveform transmission using SDRs at multiple frequencies; extensive usage of SpaceWire data bus and issue resolution; closed-loop antenna tracking system have made significant advancements on an extremely tight schedule. As the CoNNeCT system completes preparations for flight, the operations portion of the project is developing the plans for experimenter proposals and flight operation protocols. The CoNNeCT system, currently on track for a summer 2012 launch, represents significant advancements of communications technology that will pave the way for future space communication architectures.

ACKNOWLEDGEMENTS

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